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The Air Force Phillips Laboratory Multimegawatt Quasi-Steady MPD Thruster Facility

S. Castillo and D. Tilley
Phillips Laboratory, U.S. Air Force
Edwards AFB, CA

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THE AIR FORCE PHILLIPS LABORATORY MULTIMEGAWATT QUASI-STEADY MPD THRUSTER FACILITY

Salvador Castillo, Capt, USAF and Dennis L. Tilley
Phillips Laboratory
Edwards Air Force Base, California

ABSTRACT

The multi-megawatt, quasi-steady MPD thruster facility at the Air Force Phillips Laboratory is now fully operational. This operational status is the result of many modifications and improvements completed in the past year. An update of facility capabilities and operation is presented. In particular the vacuum, propellant, and electrical systems are described, followed by a description of an impulse thrust stand and diagnostics capabilities. Finally, preliminary MPD thruster test results are presented.

INTRODUCTION

In the U.S. Air Force's expanding involvement with space missions, there is a continued need for less expensive and more flexible access to space. Electric Propulsion is a promising technology to satisfy this need, particularly for orbit transfer and station keeping missions. The primary research emphasis at the Air Force Phillips Laboratory has been placed on ammonia arcjets. It is envisioned that arcjets will be operational by the end of this century. The Air Force is also interested in the research and development of magnetoplasmadynamic (MPD) thrusters for orbit transfer needs beyond the year 2000. MPD thrusters use electromagnetic forces to accelerate a plasma to typical exhaust velocities in the 10 to 50 km/sec range, depending on the propellant [1]. The high thrust density, high power handling capability, and system simplicity of MPD thrusters offer benefits over other E.P. thrusters for a variety of Air Force missions.

This paper describes the quasi-steady MPD thruster facility at the Phillips Laboratory's Electric Propulsion Laboratory (PLEPL). The term "quasi-steady" is used to describe a mode of operation where the MPD thruster is fired for a brief period (1 msec), such that the plasma state and electrical characteristics are steady, but the thermal characteristics are not. Despite this limitation, this type of thruster can be used to investigate many fundamental processes important to MPD thruster performance, which are more difficult to investigate in steady state thrusters. This facility, designed and built about ten years ago, has been used intermittently. Only within the past two years has this facility been used extensively [2,3]. During this period, many modifications and improvements have dramatically increased the reliability of this test facility. The description of this facility is split into six parts: the vacuum system, the propellant system, the electrical system, the impulse thrust stand, diagnostics platforms, and the results of a preliminary MPD thruster experiment.

VACUUM SYSTEM

The multi-megawatt quasi-steady MPD facility, also known as PLEPL Chamber #2, consists of an 8 foot diameter by 12 foot long stainless steel cylinder. The chamber, shown schematically in Figure 1, has one door, four 12 inch view ports along the sides, as well as a number of feedthroughs and pressure taps.

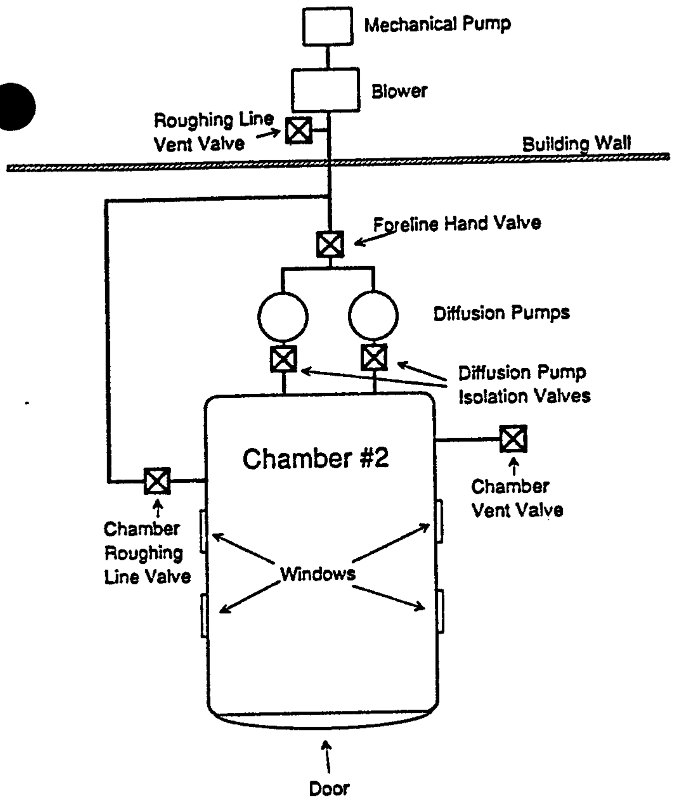

Fig. 1 Vacuum System

A Stokes mechanical pump (Model 412H-10), a Roots blower (Model 615 RGS) and two Varian 10 inch diffusion pumps (Model 0185) bring chamber pressure to low $5X10^{-4}$ Torr range before firing the thruster. The pumps also allow a return to this pressure within 1 minute after a 0.1 second gas pulse (for a mass flow rate on the order grams per second Argon). Chamber vacuum pressure is measured with a Varian 843 vacuum ionization gauge.

PROPELLANT SYSTEM

A schematic of the propellant system is shown in Figure 2. The propellant system is a choked flow pulsed gas system. A 0.25 inch propellant line feeds from a T-bottle and regulator into a 24 liter spherical plenum (nominal 15 inch diameter) located outside the vacuum chamber. An Omega pressure gage (Model # PX621-100G10V-A) measures absolute plenum pressure (typically 20 to 50 psi), and a thermocouple attached to the plenum tank measures the propellant temperature.

From the plenum, a propellant line feeds through the vacuum chamber to a Valcor solenoid valve (Model 54P1803B). The solenoid valve is located as close as possible to the MPD thruster to help reduce delay times in the gas pulse to the thruster. Immediately following the valve is a 2 millimeter diameter Fox precision orifice (Model 610284-4), which serves as a choke point for the propellant flow. A Kistler piezoelectric pressure transducer (Model 202A5) is attached downstream of the orifice. The transducer output reflects the gas pulse profile required to determine the time delay before starting the thruster. After the transducer, the propellant lines feed into 0.25 inch Tygon tubing to the MPD thruster.

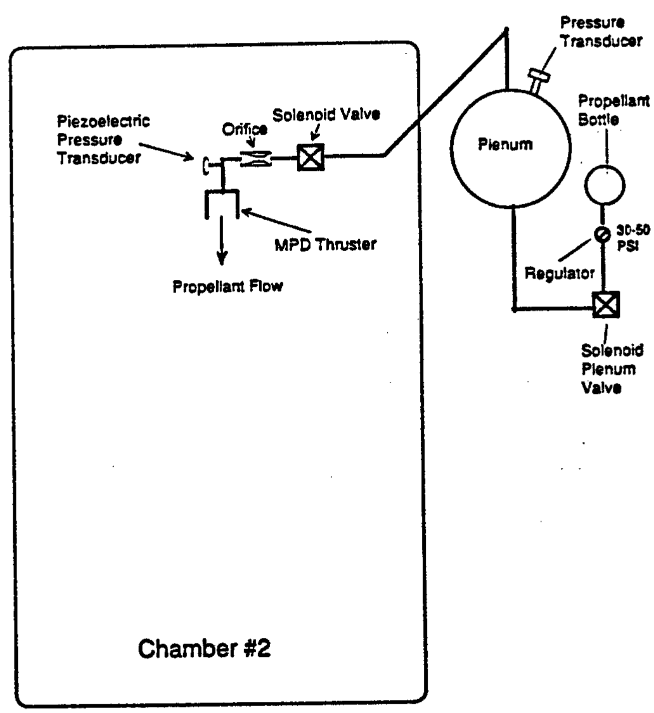

Fig. 2 Propellant System

During thruster operation, a fast acting solenoid valve opens to release an 80 millisecond gas pulse, which typically achieves steady state flow in about 15 milliseconds. It is during this steady flow that the thruster is fired. Two Rapid Systems R4000 controllers, programmed with an IBM PC based computer, regulate the timing between gas pulse initiation and thruster start.

MPD thruster testing requires accurate mass flow rate measurement and calibration. For calibration, propellant fills the plenum to maximum system pressure, and then is discharged through the thruster into the vacuum tank. The calibration theory is based on the ideal gas law, PV=nRT, which is accurate for the low pressure, low density argon used in the PLEPL tests. Mass flow, m, which is proportional to plenum pressure for choked flow, is related to the rate of change of the pressure drop by the following expression:

$$\dot{m} = -\frac{MV}{RT}\frac{dP}{dt} = kP \qquad [1]$$

where M is gas molecular weight, V is plenum volume, R is universal gas constant, T is plenum gas temperature, P is plenum gas pressure, and k is a proportionality constant. Equation 1 is based on the assumption that this process is isothermal, which was verified by experiment.

The solution to differential equation 1 is an exponential function of pressure versus time. A Tektronix DSA601 digital signal analyzer records plenum pressure versus time. The pressure history is then fit to an exponential function to yield the constant of proportionality between mass flow and plenum pressure. Mass flow calibration error is +/- 0.6 % for 1 g/sec Argon mass flow. Primary sources of error are: the pressure transducer uncertainty of +/- 0.15 psi at 100 psi, and errors introduced by the pressure curve fit.

ELECTRICAL SYSTEM

A schematic of the electrical system is shown in figure 3. The power source for the quasi-steady MPD thruster is a pulse forming network (PFN). The PFN is a ten section LC network with a nominal 0.01 ohm output impedance. Each section consists of three 2000 microfarad, 800 volt Maxwell capacitors (Model 33800) connected in parallel and a 5 turn, 0.53 microhenry inductor. Together they release a one to two millisecond current pulse at up to 30 kAmps and 400 volts, depending on the thruster used. The PFN stores approximately 20 kilojoules electrical energy, which corresponds to a maximum thruster power on the order of 10 megawatts. A Del Electronics Corp power supply (Model HPS-1-8000-3) supplies up to 8 kWe of power to the PFN.

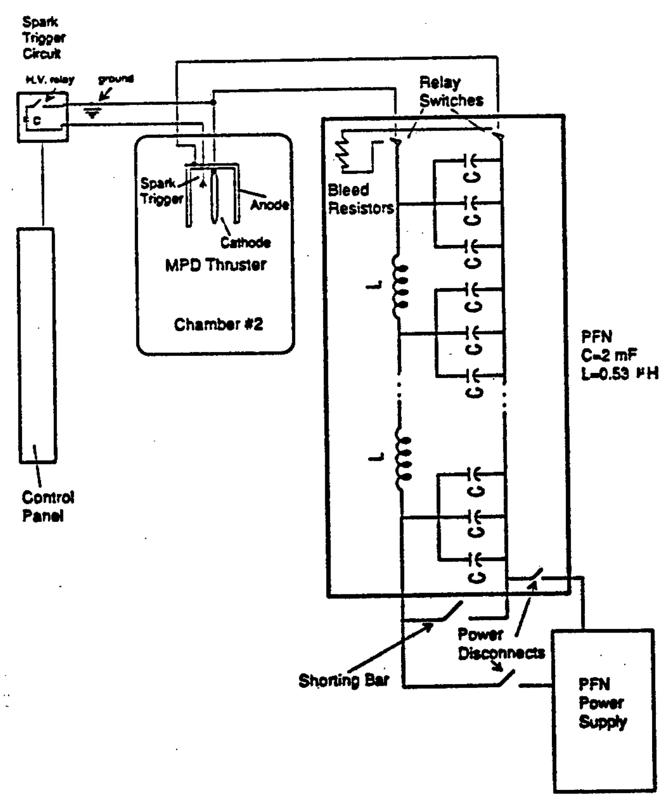

Fig. 3 Electrical System

Thruster operation is initiated in the MPD thruster via a spark trigger system. The spark trigger is a 10 mil tungsten wire fed through a thruster propellant injection hole. This spark trigger wire is used to provide an initial high voltage spark that ionizes the propellant and initiates thruster operation. The spark trigger circuit is essentially a 70 microfarad, 2.5 kilovolt Maxwell capacitor (Model 34252) charged by a Del Electronics Corp 5 kilovolt, 200 milliamp power supply (Model 5 RHPT 200-2). A high voltage relay is used to transfer the capacitor high voltage to the spark trigger.

Thruster current is measured by a Pearson Electronics current pulse transformer (Model 301X) which saturates at 20 kA for a one millisecond pulse. Voltage across the thruster is measured using two Tektronix 1000X voltage probes attached to the power feedthroughs. A Tektronix DAS 601 digital signal analyzer or a Tektronix 11403 digital oscilloscope record thruster current and voltage.

IMPULSE THRUST STAND

Thrust measurement is required for determining MPD thruster efficiency. An impulse thrust stand has been designed to accomplish this task. Initial thrust measurement will be taken with a Setra Systems accelerometer (Model 141B)- pendulum impulse stand. The accelerometer will not be used to measure thrust directly, but rather as an index to compare relative thruster acceleration to imparted thruster impulse. The thruster is held in a "saddle" which connects to two swinging Plexiglas arms of a compound pendulum. The accelerometer mounts on the bottom part of the saddle. A calibration frame will be used to swing steel balls against the thruster. Since the balls impart a known impulse to the thruster, thruster impulse can be correlated to accelerometer readings. Using this calibration approach, measurement uncertainties, such as those caused by power cable-thruster interference, can be eliminated.

An accelerometer based thrust stand may have severe electrical noise problems due to high currents involved with MPD thruster testing. An alternative thrust measurement technique is to use an LVDT (linear variable differential transducer) to measure thruster displacement instead of acceleration. This LVDT would serve the same function as the accelerometer, an index to compare against thruster impulses. From the impulse calibrations, the impulse from a firing can be correlated to total displacement. Initial thrust measurements will be made in the near future to investigate both of these approaches to thrust measurement.

DIAGNOSTICS PLATFORMS

Along with the diagnostics associated with the terminal characteristics of thruster operation, the quasi-steady MPD thruster facility has additional diagnostics platforms to investigate plasma properties in the plume and inside the thruster. There is a two-axis probe positioning system, inside of the tank, used for Langmuir and magnetic field probe studies. This system can position a probe axially 3.5 feet, and radially 1.75 feet from the thruster centerline with 1/1000th inch resolution. The probe support stand, includes a rotational stage to rotate Langmuir probes with respect to the thruster axis with 1/100th of a degree resolution. All motors are controlled by a Klinger MC4/MD4 stepper motor control system.

Also included with this facility is a Pelco (Model EH7) video camera. The camera signal is recorded with a Panasonic VCR (Model AG-1950) and viewed on a Sony monitor. In addition, the facility is equipped with a 4 X 6 foot optical table to support various spectroscopic studies. These diagnostics apparatus are fully operational and are being used in experiments currently in progress.

PRELIMINARY TESTING

At this writing, only preliminary tests were conducted on a MPD thruster. A MPD thruster schematic is shown in Figure 4. The MPD thruster consists of a 3 inch diameter, 2 inch long copper cylinder (anode) with a 0.5 inch diameter, 1 inch long 2% thoriated tungsten cathode rod. Two propellant feedlines lead into a small plenum in the thruster which allows settling of the propellant flow prior to injection into the thruster chamber. Propellant is injected through a boron nitride insulating plate, with injection holes selected to provide a uniform, symmetric flow.

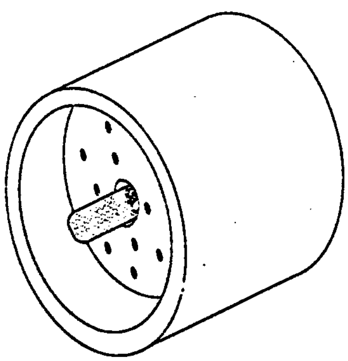

Fig. 4 MPD Thruster

Figures 5 and 6 show a sample voltage and current measurement during thruster operation. For this case, the operating current is 6.2 kA and the voltage is 100 V over a 1.6 msec period, thus verifying the quasi-steady nature of thruster operation. Furthermore, camera images have indicated that the discharge is indeed symmetric.

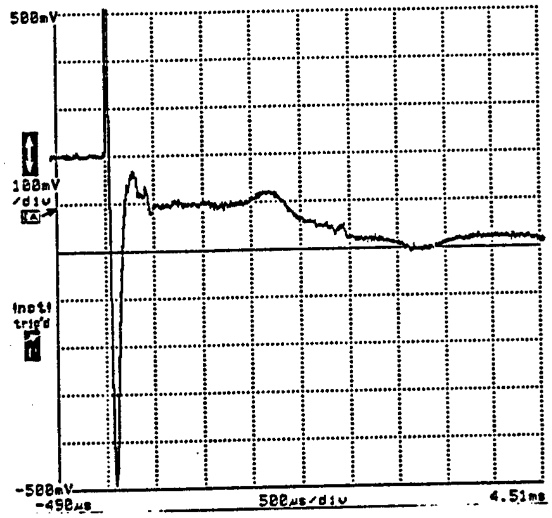

Fig. 5 Sample Voltage Trace

Fig. 6 Sample Current Trace

The thruster voltage-current characteristic is shown in Figure 7. The "s" shaped curve has been observed in previous studies [4,5,6], and is characteristic of the thruster operating in two different regimes. At low currents, the voltage scales linearly with current. As the current increases, a critical current is reached (approximately 8 kA) where the onset of large voltage fluctuations occur (the onset current). Note that the onset current value is consistent with Merfield's results for the case where the majority of the gas is injected through the annular ring around the cathode [7]. Furthermore, the voltage fluctuation magnitude increased rapidly while the current approached the onset current. As current was increased further, voltage fluctuations peaked and then fell in magnitude. This observation has also been observed by Rudolf [8]. Beyond the onset current, the V-J characteristic transitions rapidly into another linear region. This region corresponds to ablation dominated operation, which was verified by examining the thruster after the experiment.

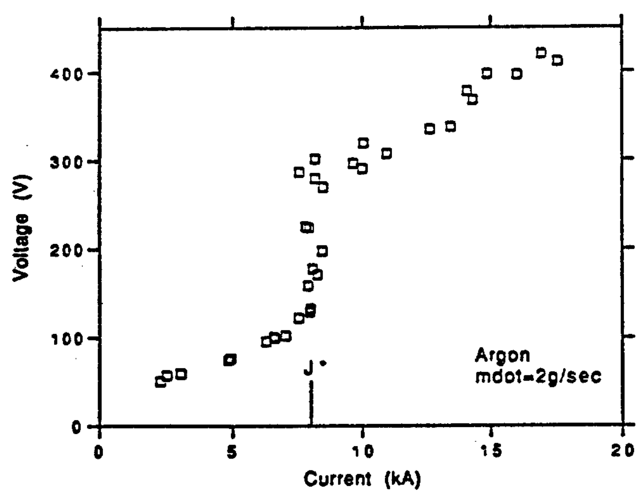

Fig. 7 Voltage-Current Characteristic

CONCLUSION

The PLEPL has completed an upgrade of its multi-megawatt quasi-steady state MPD thruster facility. In addition, preliminary measurements of the MPD thruster's terminal characteristics were completed. The facility is now ready to conduct more detailed studies of MPD thruster performance and plume diagnostics.

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